Galaxy Clustering and Baryon Acoustic Oscillations

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We present measurements of Baryon Acoustic Oscillation (BAO) distances used as an uncalibrated standard ruler that determine $\Omega_{de}(a)$, $\Omega_b$, $\Omega_m$, and $d_{BAO}^* \equiv r_s H_0 / c$; and BAO distances used as a calibrated standard ruler $r_s$ that constrains a combination of $\Sigma m_{\nu}$, $h$, and $\Omega_b h^2$. The cosmological parameters obtained in this analysis are compared with the Review of Particle Physics, PDG 2018.

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1. Introduction

At the Guadeloupe “2nd World Summit on: Exploring the Dark Side of the Universe” 2018 were presented several experiments that measure combinations of correlated cosmological parameters. The problem is how to extract the cosmological parameters from these measurements (that show mild tensions). The precise measurements of fluctuations of the Cosmic Microwave Background (CMB) temperature across almost the entire sky by the Planck experiment allows independent and precise determinations of the base set of six cosmological parameters \([1]\) under these assumptions: (i) space is flat, i.e. curvature \(\Omega_k = 0\), (ii) the dark energy density is constant, i.e. \(\Omega_{\text{de}}(a) = \Omega_\Lambda\) is independent of the expansion parameter \(a\), and (iii) neutrino masses are negligible.

At the Guadeloupe meeting I presented measurements of Baryon Acoustic Oscillation (BAO) distances used as an uncalibrated standard ruler that address (i) and (ii), and as a calibrated standard ruler that constrains a combination of \(\sum m_\nu\), \(h\), and \(\Omega_b h^2\). (We use the standard notation of the Review of Particle Physics, PDG 2018 \([2]\)). \(\sum m_\nu\) is the sum of masses of three active neutrino eigenstates assumed to be nearly degenerate, i.e. \(\sum m_\nu \approx 3m_\nu\). In the following, I will comment on these measurements, and on some minor tensions discussed at the Guadeloupe meeting. Neutrino masses measured with the Sachs-Wolfe effect, \(\sigma_8\), and the galaxy power spectrum \(P_{\text{gal}}(k)\) are discussed in a separate contribution to this conference. For details I refer the reader to the Guadeloupe talks \([3]\), and to the publications \([4]\), \([5]\), \([6]\), and references therein.

2. BAO as an uncalibrated standard ruler

From the acoustic sound horizon angle \(\theta_{\text{MC}}\) accurately measured by the Planck experiment, and 18 galaxy BAO distance measurements with Sloan Digital Sky Survey SDSS DR13 galaxies in the redshift range 0.1 to 0.7, we obtain \(\Omega_k\), \(\Omega_{\text{de}}(a) + 2.2\Omega_k\), and the adimensional standard ruler length \(d_{\text{BAO}} = r_s H_0 / c\), where \(r_s \equiv r_\alpha\) is the comoving size of the sound horizon \([4]\). The results are presented in Table 2.1 for several scenarios. Note that \(\Omega_k\) is consistent with zero, and \(\Omega_{\text{de}}(a)\) is consistent with being independent of the expansion parameter \(a\). Note also that the constraint on \(\Omega_k\) becomes tighter if \(\Omega_{\text{de}}(a)\) is assumed constant, and that the constraint on \(\Omega_{\text{de}}(a)\) becomes tighter if \(\Omega_k\) is assumed zero. From now on, we assume that \(\Omega_{\text{de}}(a) \equiv \Omega_\Lambda\) is constant, and \(\Omega_k = 0\).

With these assumptions we obtain from Table 1

\[
\Omega_\Lambda = 0.719 \pm 0.003, \quad d_{\text{BAO}} = 0.0340 \pm 0.0002, \quad \Omega_m = 0.281 \pm 0.003.
\]

(2.1)

All uncertainties are at 68% confidence with the listed assumptions. These results are robust because they are independent of any other cosmological parameter (in particular are independent of \(h\), and are independent of \(\sum m_\nu\) at the present level of accuracy), and depend on theory only through the Friedmann equation (which defines \(\Omega_k\), \(\Omega_\Lambda\), and \(\Omega_m\)). The main difficulty with these BAO measurements is the low significance of the BAO signals due to cosmological fluctuations, so that many redundant measurements were made as emphasized in the Guadeloupe talk. In particular, we measure separately \(\hat{d}_c\) for galaxy pairs approximately along the line of sight, \(\hat{d}_a\) for galaxy pairs approximately transverse to the line of sight, and \(\hat{d}_l\) for galaxy pairs at an angle to the line of sight \([4]\). Measuring the independent BAO lengths \(\hat{d}_c\), \(\hat{d}_a\), and \(\hat{d}_l\), allows a consistency check

\[
Q = \hat{d}_l / (\hat{d}_a^{0.57} \hat{d}_c^{0.43}) = 1,
\]

and also provides a direct measurement of the uncertainties. See
The observed BAO signal extends from \( \approx (148 - 11) \text{ Mpc} c H_0 / c \approx 0.0314 \) to \( \approx (148 + 11) \text{ Mpc} c H_0 / c \approx 0.0365 \) as shown in Figure 1. The only (relatively small) correction applied is for peculiar motions.

**Table 1:** Cosmological parameters obtained from 18 galaxy BAO measurements with SDSS DR13 galaxies plus \( \theta_{MC} = 0.010410 \pm 0.000005 \) from the Planck experiment in several scenarios [4]. Corrections for peculiar motions have been applied. Scenario 1 has \( \Omega_{de}(a) = \Omega_{de}[1 + w_1(1 - a)] \).

![Figure 1](image.png)

**Figure 1:** Fits to histograms of galaxy-galaxy distances \( d \), in units of \( c / H_0 \), that obtain the BAO distances \( \hat{d}_a, \hat{d}_z \), and \( \hat{d}_f \), and distribution of the consistency parameter \( Q = \hat{d}_f / (\hat{d}_a^{0.56} \hat{d}_z^{0.44}) = 1 \).

### 3. A comment on \( d_{\text{drag}} \) and \( d_\star \)

From the 18 galaxy BAO distance measurements alone, i.e. without the sound horizon angle \( \theta_{MC} \), we obtain the length of the standard ruler in units of \( c / H_0 \): \( d_{\text{drag}} = r_{\text{drag}} H_0 / c = 0.0339 \pm 0.0002 \), and \( \Omega_m = 0.284 \pm 0.014 \), see Table 4 of [4]. Adding 2 Lyman-alpha measurements obtains \( d_{\text{drag}} = 0.0340 \pm 0.0002 \) and \( \Omega_m = 0.278 \pm 0.011 \). The comoving size of the sound horizon is
Alternatively, from Table 2: Comparison of this analysis (θMC+BAO) \cite{4, 5} with PDG 2018 \cite{2} (mostly CMB from the Planck Collaboration (2015)+BAO). Ω_{de}(a) = Ω_Λ is assumed constant. Curvature Ω_k is assumed zero, except in first row. The first 4 rows of this analysis are from uncalibrated BAO (including θMC), while the last two are from calibrated BAO with z_s = 1089.9 ± 0.4.

r_s. We obtain d_s ≡ r_sH_0/c ≡ θMCχ(Ω_m,z_s) = (0.03402 ± 0.00002) · (0.285/Ω_m)^{0.4} with θMC = 0.010410 ± 0.000005 measured by the Planck experiment. χ(Ω_m,z_s)c/H_0 is the angular diameter distance at decoupling. For Ω_m = 0.281 ± 0.003 we obtain r_sH_0/c = 0.03397 ± 0.00016. We conclude that the measured r_{drag} and r_s are equal within the quoted uncertainties. For this reason we have set r_{drag} = r_s and d_{drag} = d_s = d_{BAO}. Any uncertainty due to r_{drag} ≠ r_s is not included in \cite{2}.

4. BAO as a calibrated standard ruler

The calibrated standard ruler length r_s is obtained by integrating the photon-electron-baryon plasma sound speed from primordial time until decoupling at z_s = 1089.9 ± 0.4 \cite{2}. From d_{BAO} = r_sH_0/c = 0.0340 ± 0.0002 we obtain a constraint on a combination of Σmν, h and Ω_bh^2. Reference \cite{5} takes z_{drag} = z_s = 1089.9 ± 0.4 and obtains

\[
Σmν = 0.711 - 0.335 · δh + 0.050 · δb ± 0.063 \text{ eV}, \tag{4.1}
\]

and Ω_m = 0.282 ± 0.003, where δh = (h - 0.678)/0.009, and δb = (Ω_bh^2 - 0.02226)/0.00023. Alternatively, from r_sH_0/c ≡ θMCχ(Ω_m,z_s) we obtain

\[
Ω_m^{32} · (h + 0.0255 · Σmν/eV) · (Ω_bh^2)^{-0.19} = 0.9551 ± 0.0006. \tag{4.2}
\]

From Ω_m = 0.281 ± 0.003 and Ω_bh^2 = 0.0225 ± 0.0008 at 68% confidence from Big Bang Nucleosynthesis \cite{2}, and allowing 0.06 < Σmν < 0.68 eV \cite{2}, we obtain from (4.1) or (4.2):

\[
h + 0.0255 · Σmν/eV = 0.6970 ± 0.0054, \quad \text{and} \quad h = 0.691 ± 0.012. \tag{4.3}
\]

5. Conclusions

The cosmological parameters obtained in this analysis are compared with \cite{2} in Table 2. Constraints on neutrino masses are presented in the companion talk and article in these proceedings \cite{3}.
References


